Self Seeding Pulsed Non-Linear Resonant Cavity

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Josh Hogan
620 Kingswood Way,
Los Altos, CA 94022

(650) 996 0025

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Inventor: Josh Hogan

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Background of the Invention

This invention relates to the area of optical sources which provide output radiation at a multiplicity of wavelengths. This has application in such areas as the optical communications industry where Dense Wavelength Division Multiplexing (DWDM) achieves high data rate transmission by independently modulating data on to a multiplicity of optical beams, each with a different wavelength. These optical beams are then combined and propagated down a single optical fiber. Since the different wavelengths do not significantly interfere with each other the multiple wavelengths are effectively independent communications channels.

Multiple wavelength sources are typically generated by having multiple laser diodes each designed to emit at one of the required wavelengths. Each laser diode may be fabricated so that it emits at a particular wavelength as in the case of Distributed Feed Back (DFB) lasers where the emitting wavelength is determined by the physical spacing of a distributed Bragg grating that is part of the laser diode. Alternately, laser diodes may be fabricated that are capable of emitting over a broad wavelength range and are tuned to a particular wavelength by means of precision temperature control or other means.

An alternative approach to generating multiple wavelengths is to generate a continuum of wavelengths by applying a high power single wavelength source for four wave mixing in a non-linear medium such as fiber. The non-linear or anharmonic characteristics allow the transformation of the source or pump radiation to other wavelengths.

High power is typically achieved be using a pulsed optical source so that high peak power can be attained with relatively low average power. The spectrum of the input optical pulse will be broadened to provide a continuum of wavelengths. The width of this continuum can be large if long lengths of conventional fiber are used. More recently "photonic crystal fiber" allows an extremely large continuum range to be generated with a relatively short length of fiber. A set of individual wavelengths can be generated from this continuum by routing the optical beam through a set of optical filters, such as distributed fiber gratings. This approach of generating a set of multiple wavelengths by filtering a continuum is inherently inefficient because the wavelengths filtered out essentially are wasted energy.

Another approach described at the SPIE Conference on Optical Fiber Communications, Taipei, Taiwan, July 1998 in a paper titled A Multi-wavelength WDM Source Generated by Four-Wave-Mixing in a Dispersion-Shifted-Fiber by Keang-Po Ho and Shien-Kuei Liaw is to combine the output of two continuous wave laser diodes that have slightly different wavelengths, amplify the combined signal with a high power Erbium Distributed Fiber Amplifier (EDFA) and apply this to a dispersion shifted fiber for four way mixing to produce a set or comb of wavelengths, whose wave length separation is determined by the difference in wavelength of the two seed laser diodes. Dispersion of a medium refers to the variation of the speed of propagation of radiation with wavelength within the medium. Typically the optical dispersion of a medium exhibits one or more minima at specific wavelengths around which the variation of speed of propagation with wavelength is small. Dispersion shifted media, such as, dispersion shifted fiber is designed to have zero dispersion close to the desired operating wavelength. Here, dispersion shifted medium is also intended to include the situation where a minimum coincides with the desired operating wavelength without specific modification.

This approach, however, still requires a physically long amount of dispersion shifted medium, which requires the system to be physically large which makes it more subject to environmental changes and not compatible with a requirement of being compact. It also requires the use of an expensive EDFA.

Therefore there is an unmet need for an efficient compact method and apparatus for generating a set or comb of wavelengths in manner that is compatible with low cost fabrication and which provides an integrated source of radiation at multiple wavelengths.

Summary of the Invention

This invention provides a means for generating multiple wavelengths in an integrated manner using a resonant cavity containing dispersion shifted non-linear medium and coupled to a pulsed laser source. The dispersion shifted non-linear medium is seeded by at least some of the desired wavelengths. The laser source emits radiation at a particular wavelength and is pulsed in a manner synchronously related to the round trip time of the resonant cavity. By means, such as four wave mixing, the dispersion shifted non-linear medium produces a set of discrete wavelengths. The reflective elements of the resonant cavity are designed to contain the radiation of the laser sources within the resonant cavity and to transmit an equal amount of each of the generated set of wavelengths. This invention provides an apparatus for and method of generating repetitive pulsed radiation with a multiplicity of discrete wavelengths, which includes positioning an optical processing medium in a resonant cavity with reflective elements, generating repetitive pulsed radiation from a pulsed laser source in a pump cavity with reflective elements and coupling the resonant and pump cavities.

Brief Description of the Drawings

Figure 1 is an illustration of the preferred embodiment of the invention taught herein.

Figure 2 is a detailed description of a laser source.

Figure 3 is an illustration of a laser diode power source.

Figure 4 is an illustration of a pulsed current source.

Figure 5 is an illustration of an RF signal and current pulses.

Figure 6 is an illustration of a typical reflectivity profile of an end mirror of a laser source.

Figure 7 is an illustration of a typical reflectivity profile of the output coupler.

Figure 8 is an illustration of a feedback system.

Figure 9 is an illustration of a set of wavelengths, such as the ITU grid.

Figure 10 is an illustration of a fiber based system seeded by two laser diodes.

Figure 11 is an illustration of a fiber resonant fiber cavity pumped by a pulsed laser source.

Figure 12 is an illustration of a wave guide based system with a pulsed laser source.

Detailed Description of the Invention

A preferred embodiment of the invention is illustrated in and is described with reference to Figure 1 where two cavities are shown.. The first is a fiber based resonant cavity, labeled A, that contains an optical processing medium 101, which is non-linear dispersion shifted medium. This resonant cavity is bounded by the two reflective elements 102 and 103. A pump laser cavity, labeled B, which is also a resonant cavity is bounded by the reflective elements 104 and 105. It contains a laser source 106, illustrated in more detail in Figure 2, an optical focusing element 107 and a fiber element 108.. The laser source is driven by a pulsed current source 114, also labeled PS1. The pulsed current source illustrated in more detail in Figure 5. Pulsed single wavelength radiation (also referred to as pump radiation) is generated in the pump resonant cavity. Single wavelength stabilization is accomplished by having a distributed grating filter 110 in the fiber and reflecting a portion of the filtered wavelength by the reflecting element 105 in a manner synchronized with the pulsed current source. The pulsed radiation output from the pump resonant cavity is coupled into the optical processing resonant cavity by means of a coupling element 111. As this coupled pulsed radiation propagates through the optical processing medium 101, it generates radiation at additional wavelengths by an optical mixing process, such as four wave mixing (for purposes of this application wave mixing or four wave mixing will include all types of wave mixing, including Stokes, Raman, etc.) . Radiation corresponding to some of the multiplicity of wavelengths to be generated is reflected by a distributed reflective element 112, such as a Bragg grating. These reflected wavelengths coincides with the pump radiation as it enters the resonant cavity and co-propagate with the pump radiation through the non-linear optical processing medium. The reflected wavelengths seed the process of four wave mixing and enhance the generation of these wavelengths. The process of four wave mixing causes these wavelengths to generate additional wavelengths. These additional wavelengths, in turn generate further additional wavelengths all separated by the frequency difference between the initial wavelengths. The medium is designed to be highly non linear, which facilitates four wave mixing. and it is also designed to have zero dispersion over the wavelength range being generated which allows all wavelengths to propagate through the medium at the same velocity. This process of generating additional wavelengths is enhanced by the resonant nature of the cavity, which allows multiple passes through the optical processing medium. It is also enhanced

by the synchronous relationship between the repetition rate of the cavities and the frequency separation between the seeding reflected wavelengths.

The pulsed laser sources, illustrated in Figure 2, consists of a Fabry Perot laser diode 201, with a rear flat surface 202 which forms one end mirrored surface of the resonant cavity, and has a reflective coating at the wavelength of the laser diode. The front flat surface 203 of the laser diodes is highly transmissive and has a layer of saturable absorber material 204, which is designed to shorten the temporal duration of the optical pulse. For the purpose of this application these surfaces are also referred to as facets. The optical radiation is focused into the fiber 108, using an optical focusing element 107, such as an aspheric lens or a more complex conventional system consisting of a collimating lens, an anamorphic pair and a focusing lens. The other end of the pump resonant cavity 105 is slightly reflective at the pump wavelength. The fiber 108 has a distributed imprinted diffractive gratings which filters the radiation from the pump laser. The laser source is pulsed with a repetition rate that is synchronous with the round trip time of the resonant cavity. The resonant aspect of the cavity induces the laser source to radiate only at the wavelength determined by the diffraction grating 110. Alternatively the end reflective element 105 of the pump resonant cavity can be a reflective grating which only reflects the desired pump wavelength and thus stabilizes the wavelength of the pump laser.

The laser source 106 is pulsed because high peak power enhances the transformation of source or pump radiation into the generated multiple wavelength set by four wave mixing. Several methods of pulsing can be used, including mode locking and gain switching. In mode locking all the possible modes at which the cavity can lase are phase locked to form a short optical pulse with a repetition rate determined by the round trip time of the cavity. The preferred laser source in this embodiment is a gain switched laser diode. Gain switching a laser diode may be accomplished by using a direct current to bias the laser diode close to the lasing threshold and also applying a short repetitive burst of current from an ac coupled pulsed current source. The laser diode is driven above the lasing threshold and emits a short burst of radiation. This process of maintaining the laser diode close to threshold and pulsing it above threshold is referred to as gain switching. The short current pulse may be generated, for example, by a circuit containing a step recovery diode powered by an RF signal. This approach is a method of generating a high

peak power optical pulse without the use of an expensive optical amplifier. The resulting pulse of radiation may be further shortened by enhancing the saturable absorption of the laser diode. A saturable absorber is a passive technique for reducing the temporal duration of an optical pulse. The optical pulse may be further reduced by other conventional techniques such as diffraction grating pairs, fiber gratings or non linear fiber loop mirrors.

The preferred laser source is powered by an electrical power source 114, that is illustrated in more detail in Figure 3. The power source consists of two elements. The first 301, called DC PS, is a DC power source which biases the laser diode just below threshold. The second element 302, called PCS, is a pulsed current source that is AC coupled to the laser diode through a capacitive element 303. An inductive element 304 prevents the AC current flowing to the DC power source. The pulsed current source is controlled by a reference signal 305. This arrangement causes the laser diode to operate in a gain switched mode wherein the laser diode emits an optical pulse in response to the current pulse. The short current pulse can be generated by such means as illustrated in Figure 4 where an RF signal 401, from an RF source 402 is impedance matched by matching circuitry 403 to a step recovery diode 404, called SRD. The step recovery diode accumulates the RF power during one phase and this energy is swept from the diode in the form of a short current pulse during the second phase of the RF cycle. Figure 5 describes a typical relationship between the RF signal 501 and the current pulse 502 from the step recovery diode. The laser diode typically has an inherent saturable absorption effect which compresses the optical pulse in the time domain. The pulse is further compressed be the addition of a saturable absorber layer 204 in Figure 2.

The value of the wavelengths that are reflected by the distributed reflective element 112 are selected to correspond to wavelengths on a standard grid, such as the ITU optical communications grid. the frequency difference between these wavelengths is the harmonically related to the frequency separation between all of the wavelengths on the standard grid.

Dispersion of a medium refers to the variation of the speed of propagation of radiation with wavelength within the medium. Typically the optical dispersion of a medium exhibits one or more minima at specific wavelengths around which the variation of speed of propagation with

wavelength is small. Dispersion shifted media is designed to have zero dispersion close to the desired operating wavelength. This allows all of the generated wavelengths to propagate at the same velocity within the resonant cavity. The optical processing resonant cavity A has one highly reflective end element 102, that has a reflective profile illustrated in Figure 6 and a second reflective end element 103, acting as the output coupler with a reflective profile similar to that illustrated in Figure 7. In Figure 6 the reflectivity is high for wavelengths within the desired wavelength range 601, labeled $\Delta\lambda$. In Figure 7 the reflectivity is high at the pump wavelength λ_P 701, lower at partially reflected seed wavelengths 702 labeled λ_1 and 703 labeled λ_2 . The partially reflected seed wavelengths λ_1 and λ_2 which are each different from the pump wavelength λ_P by the frequency separation 704 called $\Delta\nu$. The reflectivity decreases as the wavelength increases in distance from the center wavelengths λ_1 and λ_2. Note, other combinations of seed wavelengths could be used, for example, wavelengths, such as λ_3 705 and λ_4 706 could also be seeded by having partially reflecting gratings, or all desired wavelengths could be seeded, or only one wavelength λ_1 could be seeded. In these cases the reflection profile 707 would be adjusted appropriately. This arrangement causes the pump wavelengths and the generated set of wavelengths to remain substantially within the resonant cavity A, while wavelengths outside the desired range are discarded through the reflective element 102 and causes the output coupler 103 to emit the set of generated wavelengths with output intensities that are substantially the same or are equalized by the varying reflectivity profile 707.

The non linear characteristics of the dispersion shifted medium cause an interaction between the short optical pulse and the medium which transforms the pump radiation to a continuum of wavelengths. This non linear aspect is enhanced in medium referred to as photonic fiber or photonic crystal or photonic crystal fiber. By locating such dispersion shifted medium within a resonant cavity, the optical pump pulses circulate within the cavity and effectively extend the interaction length of the optical pulse and the dispersion shifted medium. The resonant cavity can also be designed such that the optical length of the cavity (and hence its round trip time) corresponds to a frequency which is harmonically related to the frequency separation of the desired wavelength set. The optical pump diode is pulsed with a repetition rate that is synchronous with the round trip time of the pump cavity and also is harmonically related to the

round trip time of the non-linear resonant cavity. This causes the wavelengths generated by the dispersion shifted medium to be a set of discrete wavelengths separated by a frequency of the repetition rate, rather than a continuum of wavelengths. The synchronous nature of the resonant cavity enhances the designed characteristics of the dispersion shifted medium.

The length of the resonant cavity is actively controlled by a feedback system illustrated in Figure 8. The optical pulse sequence is detected by a detector 801 and its output signal is filtered by a filter 802, such as a phase lock loop. The output of this filter is the signal 305, which is used as the reference signal of the pulsed current source PCS. The signal 305 is also applied to a frequency comparison system 803, where it is compared with a frequency reference signal to produce an error signal 806 that is used to control the optical length by such means as of temperature control. In this manner, the resonant cavity length and the repetition rate of the current pulses are stabilized to the same frequency reference. Using distributed reflective gratings as the reflective elements of the pump cavities allows the pump cavities to lock to the current pulses automatically.

The combination of partially reflecting seed wavelengths that are specific wavelengths separated by an amount related to the desired frequency separation (related to the frequency reference), synchronizing the repetition rate of the current pulse with the round trip time of the resonant cavity and locking to the frequency reference, enhances generation of the complete set of desired wavelengths. The frequency reference is chosen to be related to the desired frequency separation of the wavelength set. In this manner the frequency separation of the wavelength set can be contrived to be the frequency separation of a standard grid such as an ITU optical communications grid. The absolute values of the generated set of wavelengths are determined by the values of the partially reflected seed wavelengths and by the design of the dispersion shifted medium. An ideal set of generated wavelengths is illustrated in Figure 9, where 9 wavelengths λ_{S1} to λ_{S9} all have the same intensity, I and all are separated by the same frequency difference $\Delta\nu$ which is harmonically related to the frequency reference. Typically λ_{S4} and λ_{S6} of Figure 9 would correspond to λ_1 and λ_2 of Figure 7. The transmission characteristics of the two end

mirrors (or reflective elements) of the resonant cavity are designed to equalize the output powers of the set of generated wavelengths.

Alternative preferred embodiments are illustrated in Figures 10, 11 and 12.

In Figure 10, a single fiber based pump cavity A which includes a pulsed laser source and focusing element 1002 (similar to the source and focusing element 106 and 107 respectively, which are discussed in the preferred embodiment) and fiber 1001 with an end reflective grating 1003, to stabilize the wavelength of the laser source. The output of this cavity is coupled by a coupler 1004 into a second fiber based resonant cavity 1005 also labeled B. Radiation from two additional low power laser diodes 1006 and 1007, which are at two different wavelengths are also coupled into the second fiber based cavity 1005. This cavity contains the highly non-linear dispersion shifted fiber which transform the pump wavelength into the desired set of wavelengths by means of the low power lasers seeding wave mixing generation of these wavelengths, which in turn generate additional wavelengths by wave mixing, and so on. The cavity 1005 may also have distributed gratings designed to enhance the selection of at least some of the desired wavelengths. The mechanism for this is to preferentially reflect in a resonant manner these selected wavelengths This seeding of the wave mixing process will build up these wavelengths, which in turn will build up the adjacent wavelengths of the desired wavelength set. In this manner the desired wavelength set will be generated from a single pump laser source and the additional seeding lasers 1006 and 1007.. The output coupler 1008 of this cavity is a reflective element, either grating or coating that has a profile similar to that illustrated in Figure 7. Other aspects of this embodiment, such as a feedback system to stabilize the system to a frequency reference, are similar to aspects described in the preferred embodiment.

In Figure 11, a wavelength stabilized pulsed laser source 1101 is focused, by means of a focusing element 1102 directly into a fiber based resonant cavity comprised of optical processing medium 1103 by means an optical coupler 1104. The wavelength stabilized pulsed laser source 1101 may be similar to the pulsed laser source 106 described in the preferred embodiment, but wavelength stabilized by means of being seeded by a wavelength stabilized low power laser diode or may be

stabilized by means of being a distributed feedback laser. Alternatively the wavelength stabilized pulsed laser source 1101 may be a mode locked laser source with a pulse repetition rate harmonically related to the repetition rate of the generated pulses in the resonant cavity 1103. Other aspects of this embodiment, such as a feedback system to stabilize the system to a frequency reference, are similar to aspects described in the preferred embodiment.

In Figure 12, a system is illustrated that is similar to that illustrated in Figure 11, except that the resonant cavity is wave guide based, rather than fiber based. This contains a pulsed laser source 1201 and focusing element 1202 and a highly non-linear dispersion shifted waveguide based element 1203. Other aspects of this embodiement, such as Bragg grating elements and end reflective elements are similar in principle to the preferred embodiement. Figure 12 also illustrates an embodiement in which the pulsed laser radiation from the pump cavity are coupled by means of being co-located. Both cavities, the pump cavity and the optical processing resonant cavity are contained within the end reflective elements 1204 and 1205.

It is understood that the above description is intended to be illustrative and not restrictive. Many of the features have functional equivalents that are intended to be included in the invention as being taught. For example, the saturable absorber element could be fully integrated with the laser diode, or other pulse compression techniques, such as non-linear fiber loop or diffraction grating pairs could be used to reduce the duration of the pulse. The laser diode could, for example, be a distributed feedback laser. At least one of the mirrored elements of the resonant cavity could be etched facets, distributed feedback reflectors or distributed Bragg reflectors with deep etched grooves. Various combinations of waveguide elements and fiber based elements can be employed. Other examples will be apparent to persons skilled in the art.

The scope of this invention should therefore not be determined with reference to the above description, but instead should be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled.